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13. ABSTRACT *(Maximum 200 words)*

In this project, we have investigated a variety of problems arising in the orbital and attitude dy-namics and control of formation flying. We established important collaborations, and leveraged this AFOSR support with support from NASA and the NSF to strengthen space-related research projects at Virginia Tech. Continued work with former AFIT students (J. Beck, K. Ford, and M. Marasch) was directly tied to projects of the Space Vehicles Directorate (AFRL/VS) interest, and resulted in archival publications and conference presentations. Collaboration with Professor P. Tsiotras of Georgia Tech resulted in two conference presentations, one archival publication and an additional article in preparation. Work with graduate students at Virginia Tech resulted in ar-chival and conference publications. Publication details are given at the end of this report. This research project has direct tie-in to other projects supported by AFOSR and DARPA (University Nanosatellite Project), AFRL (PowerSail), NASA Goddard Space Flight Center (Dis-tributed Spacecraft), Universities Space Research Associates (University Nanosatellite Project), and the National Science Foundation (Analysis of Momentum Exchange in Spacecraft Attitude Dynamics and Control). We continue to attract high-quality U.S. civilian and Air Force graduate students to these pace-related projects. Furthermore, in teaching senior space design at Virginia Tech, we have supported several projects at both NASA's Goddard Space Flight Center and AFRL's Space Vehicles Directorate.

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Final Report

Project Title:	Formations of Free-Flying Gyrostat Telescopes
Contract Number:	F49620-98-1-0213
Period:	October 1997 – September 2000
Submitted By:	Christopher D. Hall Department of Aerospace and Ocean Engineering Virginia Polytechnic Institute and State University Blacksburg, VA 24061 (540) 231-2314 (540) 231-9632 (FAX) chall@aoe.vt.edu
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Table of Contents

Summary

In this project, we have investigated a variety of problems arising in the orbital and attitude dynamics and control of formation flying. We established important collaborations, and leveraged this AFOSR support with support from NASA and the NSF to strengthen space-related research projects at Virginia Tech. Continued work with former AFIT students (J. Beck, K. Ford, and M. Marasch) was directly tied to projects of the Space Vehicles Directorate (AFRL/VS) interest, and resulted in archival publications and conference presentations. Collaboration with Professor P. Tsiotras of Georgia Tech resulted in two conference presentations, one archival publication and an additional article in preparation. Work with graduate students at Virginia Tech resulted in archival and conference publications. Publication details are given at the end of this report.

This research project has direct tie-in to other projects supported by AFOSR and DARPA (University Nanosatellite Project), AFRL (PowerSail), NASA Goddard Space Flight Center (Distributed Spacecraft), Universities Space Research Associates (University Nanosatellite Project), and the National Science Foundation (Analysis of Momentum Exchange in Spacecraft Attitude Dynamics and Control). We continue to attract high-quality U.S. civilian and Air Force graduate students to these space-related projects. Furthermore, in teaching senior space design at Virginia Tech, we have supported several projects at both NASA's Goddard Space Flight Center and AFRL's Space Vehicles Directorate.

During the period of performance, the PI was General Chairman of two international conferences on satellite dynamics and control, and participated in numerous other conferences and workshops. Eleven articles and two book reviews were published in archival journals, and 14 papers were presented at conferences. In addition to serving as an Associate Editor of the AIAA *Journal of Guidance, Control, and Dynamics*, the PI received the Society of Automotive Engineers' Teetor Award, the Oak Ridge Associated Universities' Poe Award, an AIAA Best Paper Award, was promoted to Associate Professor, and was granted tenure.

One of the PI's former Ph.D. students, Kevin Ford (LtCol, USAF), was selected as a NASA shuttle pilot astronaut candidate. The present positions of all of the PI's former graduate students are listed at the end of this report.

Accomplishments/New Findings

Our primary accomplishments include the development of simulation and visualization tools for spacecraft pointing, formation flying, and kinematic blocking for PowerSail, analysis of equilibrium motions of orbiting gyrostats and gyrostats with damping mechanisms, and development of nonlinear control laws for reorienting gyrostats and tracking of targets.

Our literature review identified more than 50 technical papers over the past decade relevant to distributed sensor space systems. We divided these into three categories: single-structure systems, tethered systems, and multiple spacecraft systems. For very long baseline interferometry (VLBI) missions, only the latter two are feasible, since baselines of kilometers to thousands of kilometers are envisioned. Others are actively involved in AFOSR-sponsored tethered research (*e.g.*, Cochran and Cicci at Auburn University), which further motivates our focus on the multiple spacecraft systems, which, until recently, had received relatively little attention in the literature. Furthermore, we found no papers where the problem of controlling the attitude of individual spacecraft was considered. Most researchers focused on deep space science missions, where the formation is located far from the Earth and the objects of interest are many light-years distant. Thus the conclusions presented in these papers are not generally relevant to the problems of interest to the Air Force or other agencies interested in Earth-looking formations.

Interestingly, since our original proposal in 1997, interest in this topic has grown substantially, with a related AFOSR BAA, several papers at recent Astrodynamics Conferences, and a special session being organized for the 1999 American Controls Conference.

Our simulation and visualization tool have been developed using MatLab software, and allow generation of three-dimensional animations of specific formation-flying and coordinated pointing maneuvers. The kernel of these tools is a numerical integrator for the nonlinear equations of motion for rigid gyrostats moving about the Earth. The forces and moments acting on these spacecraft include the effects of asphericity of the Earth, atmospheric drag, and a dipole model of the Earth's magnetic field. Graphical user interfaces (GUIs) allow users to define the individual spacecraft, initial conditions, maneuvers, and so forth, in order to simulate the flight of a formation. The visualization tools include the ability to see the overlapping access areas of the spacecraft in the formation, as well as the footprints of the spacecraft's sensors. These allow us to visualize the performance of attitude control laws as a formation flies over and tracks its ground targets.

The equilibria of orbiting gyrostats in Keplerian orbits have been studied previously, but published algorithms for computing them are based on special cases, such as when a single rotor is aligned with a principal axis lying in the orbital plane. When a multi-rotor gyrostat performs a rotational maneuver, it will instantaneously pass through all of the "standard" special cases, thus this approach is not particularly useful. We have developed and implemented an algorithm, based on the Hamiltonian structure of the equations of motion, for calculating the equilibria of orbiting gyrostats (neglecting asphericity, drag, and other perturbations). This algorithm allows us to calculate equilibria in a straightforward way suitable for investigating pointing and tracking maneuvers (Hall and Beck '99, Hall '00).

In collaboration with Professor P. Tsiotras at the University of Virginia, we developed new nonlinear feedback control laws for gyrostats with internal and external torques (Hall *et al* '98). These controllers are developed as Lyapunov control laws, leading to globally, asymptotically stable motion for both reorienting a gyrostat from one orientation to another and for controlling a gyrostat to track a particular attitude motion. A novel feature of the controllers is the mixed use

of external torques (thrusters) for "coarse" control of the motion and internal torques (reaction wheel motors) for "fine" control of the motion. Several different controllers were developed, including controls with linear feedback of angular velocity and attitude errors.

These nonlinear control laws have been extended include ground target tracking and momentum-wheel-only control (Long and Hall '99), and to include power tracking for simultaneous attitude control and energy storage (Tsiotras, Chen, and Hall '99). These controllers are based on Lyapunov control theory. Although the controllers themselves are somewhat complicated, order analysis indicates that the proportional and derivative terms dominate. Thus the nonlinear system can be stabilized by a simple proportional-derivative (PD) control law.

Performance measures have been developed for formation flying missions (Hughes and Hall '99, Hughes and Hall '00). These measures allow the analyst to characterize the ability of a particular formation configuration, using a single scalar function of the parameters describing the configuration. In an N-satellite formation, there are $6N$ orbital elements characterizing the configuration. One of these, semimajor axis, must be the same for all the satellites in order for the period of all the orbits to be the same. This leaves $5N+1$ independent variables to define a formation. Our work has focused on developing lower-order approximations and comparing the resulting optimal configurations with numerical results for the higher-order systems. Additionally, we have developed a new class of formation orbits based on the nonlinear (two-body) equations of motion. These formations have some of the same advantages as the formations based on the Hill-Clohessy-Wiltshire equations, and also have the advantage of being more accurate representations of the actual dynamics.

Doppler shift effects for TechSat21 have been studied, in support of J. Herd of AFRL/SNHA. Working with a former undergraduate (Bo Naasz, now an M.S. candidate), we have developed simple approximations for the change in range-rate due to changing the separation distance, altitude, and inclination of a planar TechSat21 configuration. These effects are important because normally radar systems organize returns by frequency, with different frequencies corresponding to targets moving at different velocities relative to the radar. For a formation, the individual spacecraft in the formation will receive different return frequencies from the same target, due to the Doppler shift. The simple approximations we developed are based on exact (two-body) equations of motion and then use the separation distance as a small parameter.

We have completed an analysis of one class of equilibrium motions of orbiting gyrostats (Hall and Beck '99), where we assume the center of mass is in a circular Keplerian orbit. The approach, of course, leads to results that are equivalent to classical results, but are more easily obtained using the Hamiltonian methods. These results were extended to include additional details of the bifurcations (Hall '00).

Much of the work in this project is being applied to the nanosatellite that is being designed and built by students at Virginia Tech under the supervision of the PI. The nanosat project is part of the University Nanosatellite Program, associated with the TechSat21 Program. The nanosatellite will demonstrate formation flying using micro-pulsed plasma thrusters as orbit control actuators, while attitude control is effected by magnetic torque coils using nonlinear controllers developed at Virginia Tech. This project has been described in several conference papers (Davis *et al* '99, Campbell *et al* '00).

Personnel Supported

In addition to the Principal Investigator, five graduate students, two international undergraduate interns, and several undergraduate students have participated in related research. The graduate students are Matthew Berry, Shuvom Ghose, Steven Hughes, Chris Karlgaard, Matthew Long, Kristin Makovec, Bo Naasz, Ralph Sandfry, Jana Schwartz, Craig Stevens, and Andrew Turner. The interns are Julien Kugeler (ENSICA, Toulouse, France) and Mischa Kim (Technical University of Vienna, Austria).

Graduated Students

- Steven Hughes completed a master's thesis entitled "Formation Flying Performance Measures for Earth-Pointing Missions" in December 1999, and is currently employed at NASA Goddard Space Flight Center. Steven presented two conference papers on his research, one of which was an invited paper presented at the Richard Battin Astrodynamics Symposium, organized in honor of Dr. Battin's contributions to the spacecraft guidance field. This paper has also been selected for publication in a special issue of the *Journal of the Astronautical Sciences.*
- Matthew Long completed a master's thesis entitled "Spacecraft Attitude Tracking Control," in June 1999 and is currently a spacecraft dynamics and control engineer at Lockheed-Martin in Sunnyvale, California. Matthew presented a conference paper on his research and is currently working on a revision to submit to *Acta Astronautica.*

Continuing Graduate Students

- Kristin Makovec is in her second year of graduate study and is expected to defend her M.S. thesis on magnetic control of spacecraft attitude in May 2001. Kristin has been involved in the AFOSR/DARPA funded University Nanosatellite Project from its inception, and is co-author of an award-winning student paper entitled "Digital CMOS Cameras for Attitude Determination," presented at the AIAA/Utah State University Conference on Small Satellites, August 21–24, 2000. The paper received the 2nd Place prize of $5000.
- Jana Schwartz is in her second year of graduate study, and has been awarded an NSF Fellowship for her work on distributed control of spacecraft attitude. Jana has also been involved in the AFOSR/DARPA funded University Nanosatellite Project from its inception, and has been instrumental in formation flying analysis, systems engineering, and safety planning. Jana was selected for a summer internship at Utah State University's Space Dynamics Laboratory for Summer 2000, where she developed an integrated simulator for the formation flying dynamics and control of the Ionospheric Observation Nanosatellite Formation. A paper (co-authored by the PI and 3 other VT graduate students) describing her work has been accepted for presentation at the IEEE Aerospace Conference, March 10–17, 2001.
- Major Ralph Sandfry is an Air Force officer in the Ph.D. program, sponsored by the U.S. Air Force Academy through the Air Force Institute of Technology's Civilian Institution program. Major Sandfry has been involved in this formation flying research through directed reading, and through participation as a reviewer in NASA's internal competition for distributed spacecraft research funding. Travel for his participation in that review was supported by AFRL/VS (M. Martin). Major Sandfry's research is on analysis of bifurcations in the problem of a

gyrostat with a flexible appendage. He presented a paper on this subject at the AIAA/AAS Astrodynamics Specialists Conference, August 14–17, 2000.

New Graduate Students

- Matthew Berry is a 2000 Aerospace Engineering graduate from Virginia Tech, and has worked several semesters as a co-op at the Naval Research Laboratory in the Celestial Mechanics Group (with Dr. Shannon Coffey). He is currently working on an orbit determination project supported by NRL.
- Shuvom Ghose is a 2000 Aerospace Engineering graduate from Virginia Tech, and is participating in the PowerSail project (AFRL/VS) and is involved in the analysis of momentum exchange devices (NSF). He presented interim results of our PowerSail work at Kirtland AFB on August 2, 2000.
- Chris Karlgaard is a 1999 Aerospace Engineering graduate from University of Maryland. He has been involved in analysis of relative motion and formation flying control for the University Nanosatellite Project.
- Bo Naasz is a 2000 Aerospace Engineering graduate from Virginia Tech. As a senior, he participated in a small study on formation flying effects on Doppler shift that we completed for Jeff Herd at AFRL (Hanscom AFB). He has been involved in formation flying control law synthesis, and modeling and simulation for the University Nanosatellite Project.
- Craig Stevens is a 2000 Aerospace Engineering graduate from Virginia Tech. He has been the lead structures engineer for the University Nanosatellite Project for the past year, and has also been involved in the structural modeling for the PowerSail project.
- Andrew Turner is a 2000 Aerospace Engineering graduate from the University of Virginia, and joined our team in Summer 2000. He is working on the modeling and analysis for the attitude determination and control system for the University Nanosatellite Project.

International Interns

- Mischa Kim completed the fifth year of his Diploma Thesis for the undergraduate program in physics at Technical University of Vienna. His research topic involved studying the bifurcations leading to halo orbits about Lagrange points in the 3-body problem. He has returned to Vienna, where he will complete his examinations. He plans to return to Virginia Tech for graduate studies in 2001.
- Julien Kugeler completed his Diploma Thesis requirement for the undergraduate program in aerospace engineering at ENSICA in Toulouse, France. His research topic involved computing equilibrium attitudes of gyrostats. He is now working as a launch control engineer at the Ariane V launch facility in Kourou, Guyana.

Undergraduate Students

Several undergraduate students have been involved in research related to this project, primarily through independent undergraduate research projects and through the capstone senior spacecraft design course taught by the PI. In the year-long senior design course (Sep '98 – May '99), one group of 8 students designed a small satellite formation for Earth remote sensing, and a second group of 8 students completed a preliminary design of a nanosatellite for AFOSR's Techsat21 University Nanosatellite project. A 3rd group of students designed a single-stage-to-orbit rocket that earned the First Place prize in an AIAA Undergraduate Design Competition. The University

Nanosatellite project became a funded project under the AFOSR/DARPA University Nanosatellite Program, and has since involved literally dozens of students in Aerospace, Computer, Electrical and Mechanical Engineering.

In the Sep '99 – May '00 senior design course, 30 students were divided into 4 teams, working on 3 different tethered space system design projects. Two of these teams were collaborating with students at the Technical University of Vienna in Austria, where students were supervised by Professor Hans Troger of the Institute for Mechanics. The other two teams completed preliminary designs of a rotating tethered interferometer operating in a halo orbit about the anti-sunward Lagrangian point (L2).

This year (Sep '00 – May '01) 23 students in 3 design teams are working on 3 different projects, two of which involve formation flying, and two of which are in direct support of AFRL projects: one team is working on a PowerSail design project, and another is working on a project in support of AFRL's Solar Orbit Transfer Vehicle. The 3rd team is competing in an AIAA-sponsored design competition to design a Venus Sample Return Mission.

Publications (* indicates student)

Refereed journal articles since October 1997:

1. S. P. Hughes* and C. D. Hall, "Optimal Configurations of Rotating Spacecraft Formations," *Journal of the Astronautical Sciences*, (to appear in a special issue in honor of Richard Battin)

2. K. A. Ford* and C. D. Hall, "Flexible Spacecraft Reorientations Using Gimbaled Momentum Wheels," *Journal of the Astronautical Sciences*, (to appear)

3. P. Tsiotras, H. Shen*, and C. D. Hall, "Satellite Attitude Control and Power Tracking with Momentum Wheels," *Journal of Guidance, Control, and Dynamics* (to appear)

4. M. W. Marasch* and C. D. Hall, "Application of Flywheel Energy Storage to Solar Electric Orbital Transfers," *Journal of Spacecraft and Rockets*, Vol. 37, No. 5, 2000, pp. 645–652

5. K. A. Ford* and C. D. Hall, "Singular Direction Avoidance Steering Laws for Control Moment Gyros," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 4, 2000, pp. 648–656

6. J. A. Beck* and C. D. Hall, "Keplerian Approximation for the Motion of Rigid Satellites," *Journal of the Astronautical Sciences*, Vol. 46, No. 3, 1998, pp. 215–247

7. K. D. Hammett*, C. D. Hall, and D. B. Ridgley, "Controllability Issues in Nonlinear State-Dependent Riccati Equation Control," *Journal of Guidance, Control, and Dynamics*, Vol. 21, No. 5, 1998, pp. 767–773

8. C. D. Hall, "Escape from Gyrostat Trap States," *Journal of Guidance, Control, and Dynamics*, Vol. 21, No. 3, 1998, pp. 421–426

9. J. D. Thorne* and C. D. Hall, "Minimum-Time Continuous Thrust Orbit Transfers," *Journal of the Astronautical Sciences*, Vol. 45, No. 4, 1997, pp. 411–432

10. C. D. Hall, "Momentum Transfer Dynamics of a Gyrostat with a Discrete Damper," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 6, 1997, pp. 1072–1075

11. J. D. Thorne* and C. D. Hall, "Minimum-Time Continuous-Thrust Orbit Transfers Using the KS Transformation," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 4, 1997, pp. 836–838

Articles in preparation for submission to archival journals:

1. K. A. Ford* and C. D. Hall, "Momentum-Based Equations of Motion for a Rigid Body with Gimbaled Momentum Wheels and Flexible Appendages," *Multibody System Dynamics* (to be submitted)
2. M. R. Long* and C. D. Hall, "Spacecraft Attitude Tracking Control," *Acta Astronautica* (to be submitted)
3. C. D. Hall, P. Tsiotras, and H. Shen*, "Tracking Rigid Body Motion Using Thrusters and Momentum Wheels," *Journal of the Astronautical Sciences* (in preparation)

Theses:

Steven P. Hughes, *Formation-Flying Performance Measures for Earth-Pointing Missions*, M.S. in Aerospace Engineering, December 1999, http://scholar.lib.vt.edu/theses/available/etd-122999-103653/

Matthew R. Long, *Spacecraft Attitude Tracking Control*, M.S. in Aerospace Engineering, June 1999, http://scholar.lib.vt.edu/theses/available/etd-063099-162244/

Interactions/Transitions

a. Participation/presentations at meetings, conferences, seminars, *etc.* (* indicates student, underline indicates presenter)

- ***IEEE CCA/CACSD Joint - Control Applications/ Computer Aided Control Systems Design Conference***, Anchorage, Alaska, Sept 25–27, 2000
  M. E. Kasarda, J. Clements*, A. L. Wicks, C. D. Hall, and R. G. Kirk, "Effect of Sinusoidal Base Motion on a Magnetic Bearing"

- ***American Institute of Aeronautics and Astronautics/Utah State University Conference on Small Satellites***, August 21–24, 2000, Logan, Utah
  Advised graduate student (Kristin Makovec) who was awarded the 2nd Place prize ($5000) for her paper "Digital CMOS Cameras for Attitude Determination," co-authored with two other students

- ***American Institute of Aeronautics and Astronautics/American Astronautical Society Astrodynamics Specialist Conference***, August 14–17, 2000, Denver, Colorado
  Presentation
  R. A. Sandfry* and C. D. Hall, "Motion of a Gyrostat with a Discrete Damper," 2000 AIAA/AAS Astrodynamics Specialists Conference, Denver, CO, Aug 14–17, 2000. This paper was nominated for Best Paper Award.
  Other participation
  Session Chair for *Attitude Determination and Control*

Member of Astrodynamics and Space Flight Mechanics Technical Committees

- ***US-European Celestial Mechanics Workshop***, July 3–7, 2000, Poznan, Poland

Presentation

C. D. Hall, "Attitude Dynamics of Orbiting Gyrostats," Invited Paper, US – European Celestial Mechanics Workshop, Adam Mickiewicz University in Poznan, Poland, 3 – 7 July 2000. This paper is being considered for publication in a special issue of *Celestial Mechanics and Dynamical Astronomy.*

Other participation

Session chair for *Satellite Constellations*

- ***The Richard H. Battin Astrodynamics Symposium,*** March 20–21, 2000, Texas A&M University, College Station, Texas

Presentation

S. P. Hughes* and C. D. Hall, "Optimal Configurations of Rotating Spacecraft Formations," Invited Paper, Richard H. Battin Astrodynamics Symposium, Texas A&M University, College Station, TX, Mar 20–21, 2000. This paper was also accepted for publication in a special issue of the *Journal of the Astronautical Sciences*.

- ***American Astronautical Society/American Institute of Aeronautics and Astronautics Space Flight Mechanics Meeting***, January 23–26, 2000, Clearwater, Florida

Presentation

M. Campbell, R. R. Fullmer, and C. D. Hall, "The ION-F Formation Flying Experiments," AAS/AIAA Space Flight Mechanics Meeting, Clearwater, FL, Jan 23–26, 2000

Other participation

AAS General Chair for conference

Member of Astrodynamics and Space Flight Mechanics Technical Committees

Chair of John V. Breakwell Student Travel Award Subcommittee of the American Astronautical Society Space Flight Mechanics Committee. This award funds student travel to AAS/AIAA conferences for up to 5 students per year.

- ***American Institute of Aeronautics and Astronautics/Utah State University Conference on Small Satellites,*** August 23–26, 1999, Logan, Utah

Presentation

N. Davis, J. DeLaRee, C. D. Hall, W. L. Stutzman, and W. A. Scales, "Virginia Tech Ionospheric Scintillation Measurement Mission," Paper SSC99-III-2 (10 pages)

Other participation

Judge for *University Student Scholarship Competition*, which awarded more than $20,000 to undergraduate and graduate students presenting papers on small satellites

- ***American Institute of Aeronautics and Astronautics/American Astronautical Society Astrodynamics Specialist Conference***, August 15–19, 1999, Girdwood, Alaska
  Presentations
  C. D. Hall and J. A. Beck, "Relative Equilibria of Orbiting Gyrostats," Paper AAS 99-459 (15 pages)
  P. Tsiotras, H. Shen*, and C. D. Hall, "Satellite Attitude Tracking Control and Power Tracking with Momentum Wheels," Paper AAS 99-317 (12 pages).
  Other participation
  Session Chair for *Attitude Dynamics and Control: Applications*
  Chair of John V. Breakwell Student Travel Award Subcommittee of the American Astronautical Society Space Flight Mechanics Committee. This award funds student travel to AAS/AIAA conferences for up to 5 students per year.

- ***American Society of Mechanical Engineers Mechanics & Materials Conference***, June 27-30, 1999, Blacksburg, Virginia
  Session Co-Chair for *Noise and Vibration Control for Launch Vehicles and Satellite Applications*

- ***American Society for Engineering Education Conference and Exposition***, June 20-23, 1999, Charlotte, North Carolina
  Presentation
  C. D. Hall, "Laboratory Instruction in Undergraduate Astronautics," Session 2302: Putting Space into Aerospace Engineering (11 pages)

- ***Flight Mechanics Symposium***, May 18–20, 1999, Goddard Space Flight Center, Greenbelt, Maryland
  Presentations
  S. P. Hughes* and C. D. Hall, "Mission Performance Measures for Spacecraft Formation Flying," 1999 Flight Mechanics Symposium, pp. 309–318
  M. R. Long* and C. D. Hall, "Attitude Tracking Control for Spacecraft Formation Flying," 1999 Flight Mechanics Symposium, pp. 319–332

- ***American Astronautical Society/American Institute of Aeronautics and Astronautics Space Flight Mechanics Meeting***, February 1998, Monterey, California:
  Presentation
  M. W. Marasch* and C. D. Hall, "Flywheel Energy Storage Applied to Solar Electric Orbital Transfers" AAS Paper No. 98-204
  Other participation
  Session Chair, Estimation Theory

- ***American Institute of Aeronautics and Astronautics/American Astronautical Society Astrodynamics Specialist Conference***, August 1998, Boston, Massachusetts

  Presentations

  K. A. Ford* and C. D. Hall, "Singular Direction Avoidance Steering Laws for Control Moment Gyros" AIAA Paper No. 98-4470

  C. D. Hall, P. Tsiotras, and H. Shen*, "Tracking Rigid Body Motion Using Thrusters and Momentum Wheels" AIAA Paper No. AIAA-98-4471

  Other participation

  AIAA General Chair for the conference

- **Workshop Participation**

  "PowerSail Umbilical Interactions," AFRL PowerSail Technical Interchange Meeting, Albuquerque, NM, August 2, 2000

  "Virginia Tech Ionospheric Scintillation Measurement Mission," AFRL/DARPA University Nanosatellite Kickoff Meeting, Albuquerque, NM, Jan 19, 1999

  "Modeling and Simulation of Formation Flying," Distributed Spacecraft Control Workshop, Goddard Space Flight Center, Greenbelt, MD, Dec 17, 1998

  "Dynamics and Control in Formation Flying," AFRL Formation Flying and Micro-Propulsion Workshop, Lancaster, CA, Oct 20, 1998

  "Flywheel Research at Virginia Tech," 1998 AFRL/NASA Aerospace Flywheel Workshop, Albuquerque, NM, Oct 7, 1998

- **Other Presentations**

  "Dynamics and Control in Satellite Formation Flying," Invited Lecture, University of Colorado, Colorado Springs, Colorado, March 17, 2000

  "Design of Small Spacecraft," Invited Lecture, USAF Academy, Colorado Springs, Colorado, March 16, 2000

  "Satellite Systems for Earth Observations," Virginia Tech Geography Department, January 31, 2000

  "Space Education and Research," BWX Technologies, Lynchburg, VA, Jul 13, 1999

  "Space Exploration," Rural Retreat Cub Scout Pack Blue and Gold Banquet, Rural Retreat, VA, Apr 15, 1999

  "Virginia Tech Ionospheric Scintillation Measurement Mission," College of Engineering Open House, Blacksburg, VA, Mar 29, 1999

  "Satellite Systems for Earth Observations," Virginia Tech Forestry Department Seminar, Blacksburg, VA, Mar 26, 1999

  "Military Space," Virginia Tech Air Force ROTC Detachment, Blacksburg, VA, Mar 16, 1999

  "Dynamics and Control in Satellite Formation Flying," Invited Lecture, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, NY, Nov 18, 1998

"Attitude Dynamics and Control of Spacecraft Using Momentum Wheels," Invited Lecture, Department of Mechanical, Aerospace and Nuclear Engineering, University of Virginia, Charlottesville, Virginia, November 1997

b. Consultative and advisory functions

- **Air Force Research Laboratory**

  Provided technical evaluation and discussion on flywheel energy storage systems for spacecraft. Primary contacts: Dr. Jerry Fausz and Capt Tim Murphy. Interaction has been through email and telephone calls. On October 6–8, presented at the Aerospace Flywheel Workshop being organized by Dr. Fausz. My co-presenter was Dr. Mary Kasarda from Mechanical Engineering at Virginia Tech. We discussed our joint work on the effects of base motion on the performance of magnetic bearings.

  Provided technical analysis of Doppler shift for formation flying of TechSat21 to J. Herd, AFRL/SNHA. This analysis involved a then-senior undergraduate student, Bo Naasz. Mr. Naasz wrote and presented a paper entitled "Range-Rate Processing for Formation Flying Radar Satellites," at the 2000 AIAA Student Conference at Pennsylvania State University.

  Principal Investigator in the University Nanosatellite Program. Advising a group of undergraduate and graduate students designing and building a 15 kg spacecraft that will be launched on the space shuttle in 2002. Spacecraft will demonstrate several new technologies including autonomous formation flying.

  Contributing to the AFRL/VS PowerSail project, in collaboration with Troy Meink and Kim Luu of AFRL/VS. Support to the project includes graduate student activity in modeling and simulation of umbilical interactions as well as undergraduate student involvement through at senior design project in academic year 2000-2001.

  Supervising a student design project in support of AFRL/VS Solar Orbit Transfer Vehicle project. This project is being done in academic year 2000-2001, with the cooperation of the program manager, Russell Partch, AFRL/VS, and one of the contractors, BWX Technologies, Lynchburg, Virginia.

  Reviewed three dynamics and control proposals submitted to AFOSR.

- **Goddard Space Flight Center, Flight Dynamics Laboratory**

  Provided technical analysis and support on their formation flying research activities. Contact led to research contract for student support directly relevant to this AFOSR project. Principal contact: Mr. David Folta, Flight Dynamics Engineer. Support has involved review of proposals as well as direct support through tool development and formation flying analysis. Three graduate students have been supported and have worked at Goddard as a result of this involvement.

  Supervised a student design project in support of the Leonardo project. This project was completed in the 1998-1999 academic year. The Leonardo mission involves a formation of Earth remote sensing satellites to measure the radiation leaving the Earth's atmosphere.

  Supervised a student design project in support of the SPECS project. This project (Submillimeter Probe of Early Cosmic Structure) was completed in the 1999-2000

academic year. The SPECS mission involves a rotating tethered interferometer in a halo orbit about the L2 libration point.

- **Universities Space Research Associates**
  Consulted on the development at Honeywell of an integrated power and attitude control system using high-speed flywheels. This project is funded by AFRL.

New Discoveries, Inventions, or Patent Disclosures

None.

Honors/Awards

Research Grants:

Flight Safety of the Virginia Tech Ionospheric Scintillation Measurement Mission, Universities Space Research Associates, $34,725, FY00-01

Leonardo Mission Unique Orbits, NASA Goddard Space Flight Center, $17,250, FY00

Umbilical Coupling of the Motion of a Spacecraft and a PowerSail, Air Force Office of Scientific Research, $34,157, FY00

ION-F: A Space-Based Testbed for Distributed Formation Control Using the HokieSat Nanosatellite, NASA Goddard Space Flight Center, $127,000, FY00-02

Analysis of Momentum Exchange in Spacecraft Attitude Dynamics and Control, National Science Foundation, $147,957, FY00-02

Virginia Tech Ionospheric Scintillation Measurement Mission, Universities Space Research Associates, $18,600, FY99-00

Virginia Tech Ionospheric Scintillation Measurement Mission, AFOSR/DARPA, $100,000, FY99-00

Modeling and Simulation of Formation Flying, NASA Goddard Space Flight Center, $85,265, FY99

Rotational Dynamics and Control of Magnetic Bearing Systems, Oak Ridge Associated Universities, $5,000, FY99

Spacecraft Simulator, ASPIRES Grant, $32,512, FY98

Using Satellites in Teaching Undergraduate Astrodynamics, Center for Excellence in Undergraduate Teaching Grant, $3100, FY98

Satellite Tracking Laboratory, SCHEV, $10,172, FY98

Associate Fellow, American Institute of Aeronautics and Astronautics, October 1997

Associate Editor, *AIAA Journal of Guidance, Control, and Dynamics*

Invited Paper. C. D. Hall, "Attitude Dynamics of Orbiting Gyrostats," Invited Paper, US – European Celestial Mechanics Workshop, Adam Mickiewicz University in Poznan, Poland, 3 – 7 July 2000. Also being considered for publication in a special issue of *Celestial Mechanics and Dynamical Astronomy.*

Invited Paper. S. P. Hughes* and C. D. Hall, "Optimal Configurations of Rotating Spacecraft Formations," Richard H. Battin Astrodynamics Symposium, Texas A&M University, College Station, TX, Mar 20–21, 2000, (also accepted for publication in a special issue of *Journal of the Astronautical Sciences* in honor of Richard Battin)

AIAA Astrodynamics Best Paper Award, presented at the AIAA Astrodynamics Specialist Conference, August 1998, Boston, Massachusetts. This award was for a paper presented at the August 1997 Astrodynamics Specialist Conference in Sun Valley, Idaho:

> J. A. Beck* and C. D. Hall, "Keplerian Approximation for the Motion of Rigid Satellites," *Advances in Astronautical Sciences*, Vol. 97, No. 2, 1998, pp. 1187–1216, AAS Paper 97-678. (also published in the *Journal of the Astronautical Sciences*, Vol. 46, No. 3, 1998, pp. 215–247)

Oak Ridge Associated Universities Ralph E. Powe Junior Faculty Enhancement Award, 1998

Society of Automotive Engineers Ralph R. Teetor Educational Award, presented at the World Aviation Congress, October 1997, Anaheim, California.

The Aerospace and Ocean Engineering Department received the University's Exemplary Department Award for effective integration of undergraduate students into research programs. The PI made a presentation to the College of Engineering's Committee of 100 Advisory Board in October 1999 on undergraduate student participation in space-related research.

Current Positions Held by Master's and Doctoral Advisees

R. Kevin Adams, M.S., Major, USAF, Assistant Operations Officer (A-10 Pilot), 75th Fighter Squadron, Pope AFB, North Carolina

Jeffrey A. Beck, Ph.D., Major, USAF, Director, Defense Support Satellite Ground Systems, Los Angeles AFB, California

Kevin D. Benedict, M.S., Captain, USAF, Mission Manager for the Tri-Service Experiment Satellite Program, Kirtland AFB, New Mexico

David P. Blanks, M.S., Captain, USAF, Air Officer Commanding, USAF Academy, Colorado

Anne E. Chinnery, M.S., Deputy Program Manager, Scorpius Expendable Launnch Vehicle, Microcosm, Inc., Torrance, California

Paul J. Cotter, M.S., Captain, USAF, Launch Officer, Cape Canaveral Air Force Station, Florida

Jules F. Desamours, M.S., Captain, USAF, Space Systems Engineer, Defense Support Program Satellite, Buckley Air National Guard Base, Colorado

Steven A. Fischer, M.S., Captain, USAF, Space Systems Analyst, National Air Intelligence Center, Wright-Patterson AFB, Ohio

Kevin A. Ford, Ph.D., Lieutenant Colonel, USAF, Astronaut Pilot Candidate, Johnson Space Flight Center, Houston, Texas (Formerly Deputy Director of Research (F-15 Test Pilot), USAF Test Pilot School, Edwards AFB, California)

Dwight D. Fullingim, M.S., Captain, USAF, AF Operational Test and Evaluation Center, Kirtland AFB, New Mexico

Joel J. Hagan, M.S., Captain, USAF, F-22 Flight Test Engineer, USAF Test Pilot School, Edwards AFB, California

Brady P. Hauboldt, M.S., Captain, USAF, Executive Officer, Imaging Intelligence, National Reconnaissance Office, Washington, DC

Steven P. Hughes, M.S., Aerospace Engineer, Guidance, Navigation and Control Center, NASA Goddard Space Flight Center, Greenbelt, Maryland

Brian L. James, M.S., Captain, USAF, AF Operational Test and Evaluation Center, Kirtland AFB, New Mexico

Stewart J. Kowall, M.S., Lieutenant Colonel, USAF, Assistant Air Attaché to the US Embassy, Tel Aviv, Israel

Anthony M. Logue, M.S., Captain, USAF, Space Systems Engineer, Air Force Space Command, Peterson AFB, Colorado

Matthew R. Long, M.S., Software Engineering Associate/Attitude and Orbit Control, Lockheed Martin Missiles and Space, Sunnyvale, California

Mark W. Marasch, M.S., Captain, USAF, Solar Orbit Transfer Vehicle Project Engineer, Air Force Research Laboratory, Kirtland AFB, New Mexico

Cynthia A. Provost, M.S., Captain, USAF, Chief of Tactical Operations, 566 Operations Support Squadron, Denver, Colorado

Ralph A. Sandfry, M.S., Major, USAF, Ph.D. candidate, Aerospace and Ocean Engineering, Virginia Tech

Gregory W. Schultz, M.S., Captain, USAF, Chief of Architecture Integration, National Reconnaissance Office, Washington, DC

William A. Seeliger, M.S., Captain, USAF, Space Operations Officer, Schriever AFB, Colorado

Stephen J. Skotte, M.S., Captain, USAF, Space Systems Engineer, Space and Missile Systems Center, Los Angeles AFB, California

James D. Thorne, Ph.D., Major, USAF, Chief of National Aerospace Strategy, Headquarters USAF, Washington, DC

Raymond Tsui, M.S., Captain, USAF, Command Military Construction Programmer, Headquarters Air Force Space Command, Peterson AFB, Colorado

James M. Valenti, M.S., Captain, USAF, Space Systems Analyst, AF Technical Applications Center, Patrick AFB, Florida

Jörg D. Walter, M.S., Captain, USAF, Space Systems Analyst, AF Technical Applications Center, Kirtland AFB, New Mexico

Kevin J. Walker, M.S., Captain, USAF, Missile Combat Crew Member, 319 Missile Squadron, F.E. Warren AFB, Wyoming

John W. Wong, M.S., Captain, USAF, Space Systems Analyst, Systems Engineering and Integration Division, Space and Missile Systems Center, Los Angeles AFB, California

Michael L. Zywien, M.S., Lieutenant Colonel, USAF, Chief of Integration and Test for Joint Airborne Signal Intelligence Project Office, Wright-Patterson AFB, Ohio